Section Life Cycle Management

Summaries from Papers in Gate to EHS/LCM

Life Cycle Assessment of Fuel Cell Vehicles
A Case Study Summary

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Life Cycle Assessment (LCA), or 'well to wheels' in transportation terms, involves some subjectivity and uncertainty, especially with new technologies and future scenarios. To analyze lifecycle impacts of future fuel cell vehicles and fuels, the Fuel Upstream Energy and Emission Model (FUEEM) was developed within the Fuel Cell Vehicle Modeling Program at the Institute of Transportation Studies – Davis. The FUEEM project pioneered two specific new ways to incorporate and propagate uncertainty within an LCA analysis. First, the model uses probabilistic curves generated by experts as inputs and then employs Monte Carlo simulation techniques to propagate these uncertainties throughout the full chain of fuel production and use. Second, the FUEEM process explicitly involves the interested parties in the entire analysis process, not only in the critical final review phase. The methodology for the data treatment was presented early in this journal (Contadini et al. 2002) and the simulation techniques can be founded in Contadini (2002).

To demonstrate the FUEEM process, a life cycle inventory and assessment (for greenhouse gases) was conducted for three Fuel Cell Vehicle technologies concepts, hypothetically operating in the South Coast California Air Basin (SCAB) in the year 2010 and beyond. The analyzed vehicle concepts are Direct Hydrogen Fuel Cell Vehicles (DHFCV), Indirect Methanol Fuel Cell Vehicles (IMFCV), and Indirect Hydrocarbon Fuel Cell Vehicles (IHFCV). The main results and a more detailed explanation of the variables were published in the Internet Journal 'Gate to EHS', area Life Cycle Management (Contadini and Moore 2002). The objective of this paper is to present a summary of that original paper.

The requested fuels for the vehicles (hydrogen, methanol and hydrocarbon) are all based on the natural gas pathway. Natural gas (NG) is the 'most feasible' near-term feedstock to produce hydrogen in areas where electricity is expensive, such as California, the US and Europe. A similar conclusion was reached with respect to methanol production when methanol is produced from inexpensive, large and remote NG reserves, such as Chile, Trinidad-Tobago, Malaysia, etc. For indirect-hydrocarbon fuel cell vehicles, Fischer Tropsch Naphtha (FTN) is chosen as the hydrocarbon fuel, due to the potential need for a clean (sulfur free) and easier-to-reform (saturated hydrocarbon) fuel for FCVs.

FUEEM provides the inventory values for the energy consumption disaggregated into fossil fuel and petroleum consumption as well as the total consumption. It also assesses the major urban air criteria emissions and greenhouse gases (NO_x, NMOG, CO, PM_{10}, SO_x, CH_4, N_2O, CO_2 and $CO_{2\text{-equivalent}}$) disaggregated into three different areas selected by the analyst. The three chosen areas are South Coast Air Basin – SCAB (analyzed area), the state of California (without SCAB), and the total emissions including the emissions generated in the rest of the world.

The operational unit of the analysis is kilometers driven over the vehicle's life. The energy requirement comparison is done in terms of mega Joule of energy required over the entire life cycle per kilometer driven (MJ / km). High heating values are used through the entire calculation. The air emissions comparison is done in terms of milligrams of pollutants released over the entire life cycle per kilometer driven (mg/km). For the CO_2 inventory and for the assessment of the greenhouse gases in terms of $CO_{2\text{-equivalent}}$ the comparison is done in terms of grams of pollutant per kilometer driven (g/km). The global warming assessment phase uses deterministic values of one-hundred-year global warming potentials (GWP), as suggested by the International Panel of Climate Change (IPCC 2001) or, as an option, uses probabilistic curves representing the economic damage index (EDI). The fuel upstream analysis is accomplished in terms of grams of pollutant per energy content, Giga Joule (GJ), of the fuel delivered to the vehicle (kg of pollutant per km for the CO_2 case) or energy requirement (GJ) per energy content of the fuel delivered to the vehicle (GJ).

Similar to most of the other robust transportation models, the boundaries here include the operational phase of the activities from feedstock extraction to the vehicle operation. The activities or stages include the feedstock extraction, processing, storage, and transportation as well as the fuel production, storage, transportation/distribution, and fuel consumption at the vehicle. The secondary fuels and electricity consumed in each activity are also considered from the feedstock extraction to the final use.

Since Fuel Cell Vehicles (FCVs) are a new technology in development, the time frame of 2010 was discussed and adopted as the referential for the technology to be in place, in circumstances similar to a well-established market.

The vehicle fuel efficiency assumptions represent a mid-size passenger fleet of fuel cell vehicles running in the SCAB area about 2010 and they try to capture the real world operation, as opposed to the certification drive cycle. These vehicle assumptions are partially based on the results of running the FCVSim model developed by the Fuel Cell Vehicle Modeling Program (Hauer 2001). To represent the real world drive conditions a
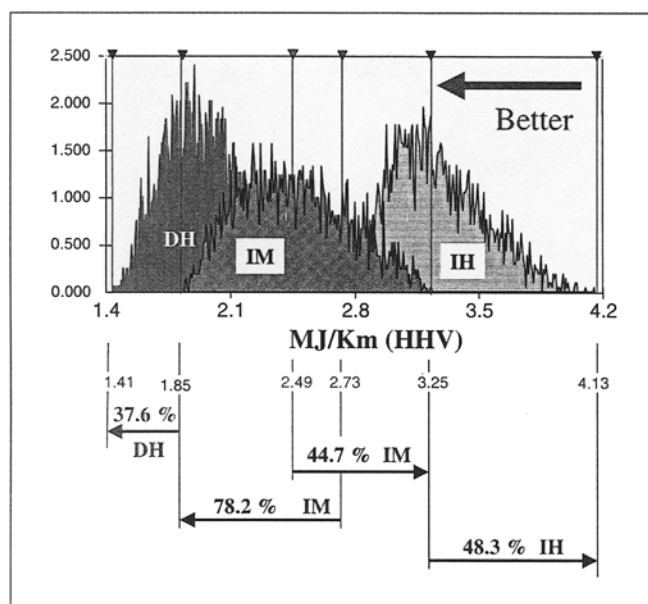
Fig. 1: Life cycle result of the total energy requirement

Fig. 2: Life cycle result of the NO$_x$ emissions within SCAB

mixed result of simulations, considering the US06 drive cycle and a faster (1.25 factor) combined EPA cycle, was used.

The total energy requirement (TE$_{req}$) results show that, in general terms, the operation of a direct hydrogen fuel cell vehicle (DHFCV) has a higher possibility of requiring (or consuming) less energy in the entire life cycle than the other technologies considered – the indirect methanol fuel cell vehicle (IMFCV) and the indirect Fisher Tropsch naphtha fuel cell vehicle, or simplified as indirect hydrocarbon (IHFCV).

On the other hand, based on the uncertainty analysis done, only 37.6% of the direct hydrogen (DH) scenarios are more efficient, or consume less energy in the life cycle (1.41 MJ$_{req}$/km • DH-TE$_{req}$ < 1.85 MJ$_{req}$/km) than any of the indirect methanol (IM) scenarios considered. For the rest of the hydrogen scenarios (62.4%) it is possible to find at least one methanol scenario that consumes equal or less energy (1.85 MJ$_{req}$/km • DH-TE$_{req}$ • 2.49 MJ$_{req}$/km) than the hydrogen scenarios. The analyses also show that 44.7% of the indirect methanol scenarios are less efficient, or consume more energy in the life cycle than any hydrogen scenario considered (2.49 MJ$_{req}$/km < IM-TE$_{req}$ • 3.25 MJ$_{req}$/km). For all scenarios, the direct hydrogen cycles are more efficient (or consume less energy) than the indirect hydrocarbon cycles. See **Fig. 1** for a graphical representation of the curves.

The same discussion applies to the indirect methanol fuel cell vehicle and the indirect hydrocarbon scenarios.

The results of the greenhouse gases assessment, in terms of grams of CO$_{2\text{-equivalent}}$ per kilometer driven, are very similar to the total energy requirement results. The reason is that the bulk of the energy consumption is fossil fuel consumption which produces CO$_2$ when combusted.

Several criteria pollutants were analyzed related to their area of occurrence. The results showing these pollutants emitted within SCAB highlight a great potential for each fuel cell vehi-

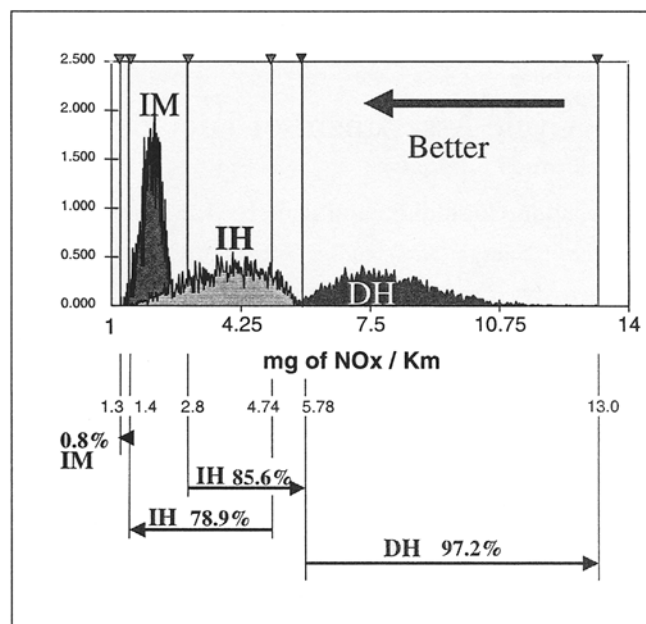cle technology to improve air quality in urban areas. For example, the emissions of nitrogen oxides (NO$_x$) inside SCAB area are low for the three cycles analyzed. In general terms, the operation of the indirect methanol fuel cell vehicle may have the highest probability for the lowest life cycle emissions (1.3 mg/km ≤ IM-NO$_{x\text{-SCAB}}$ ≤ 2.8 mg/km), followed by the indirect hydrocarbon fuel cell vehicle operation (1.4 mg/km ≤ IH-NO$_{x\text{-SCAB}}$ ≤ 5.78 mg/km), and then by the direct hydrogen fuel cell vehicle operation (4.74 mg/km ≤ DH-NO$_{x\text{-SCAB}}$ ≤ 13.0 mg/km). **Fig. 2** presents these curves. The majority of these emissions come from the activities that burn natural gas (power generation and compression station equipment) and diesel (trucks and port activities) and, in the hydrogen case, they are also related to the scenarios selected by the expert network, where the hydrogen production plants are most likely placed close to the end-user retail market, and thus within SCAB.

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